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PROGRESS IN EXPLOSIVE ROCK PENETRATION

by

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ABSTRACT

As part of the Eastern Gas Shales Project, the Los Alamos Scientific Laboratory is investigating the application of improved shaped charges lined with uranium metal to the open hole explosive stimulation of gas in tight, carbonaceous shales. Above ground testing methods for charges having several pounds of explosive were developed and used to determine optimum thickness of uranium liner in hemispherical charges as a reference design. Tests with encased core specimens were made with commercial perforator charges lined with copper cones to intercompare the penetrabilities of synthetic grouts with shales and reference rock types. Advanced charge design using tapered thickness of the smoothly concave liner to achieve controlled, on-axis collapse and high-performance jets are analyzed by hydrodynamic computer methods prior to selection for fabrication and experimental firing. Remaining problems include determination of threshold velocity for penetration of rock, sensitivity of rock penetration to charge standoff, and the coupling of explosive rock penetration to the stimulation characteristics of shale formations.

INTRODUCTION

Having at our disposal newly developed capability to design high-performance explosive shaped charges with hemispherical liners of uranium metal [illegible] we are addressing the challenge of [illegible] applicable to those tight, [illegible] formations [illegible] the Devonian shales of the Appalachian [illegible] Basins [illegible] Eastern [illegible] States [illegible] history [illegible] hole [illegible] stimulation [illegible] economically [illegible] tensive [illegible] and [illegible] hydraulic [illegible] from upward [illegible] 100 [illegible] stimulations are [illegible] least [illegible] with [illegible] Difficulties [illegible] shale are [illegible] (1) [illegible] which [illegible] of the injected water [illegible] proppant, and (2) the extreme vertical extent ($\sim 10^2$ feet) of the unseparated shale strata, which allows little knowledge or preventive control of unproductive upward or downward excursion of the fracture, at the expense of the desired horizontal propagation at the depth of the casing perforations.

There are physical effects which detract from the effectiveness of explosive stimulation, also, with greater or lesser degrees of certainty and severity. Probably the most certain aftereffect of open hole explosive stimulation is rubble blocking the borehole for some considerable depth upward from TD. Tedious removal of this rubble would be required if the well is to produce or accumulate liquids (either hydrocarbons or water). The Devonian Shales in many localities, however, are inherently free of liquid production, and gas recovery through the rubble has often been successful. The other primary hazard detracting from the success ratio of explosive stimulation is damage to casing, and conservative stemming practices offer the best countermeasure. The adverse effects of explosives upon wellbore walls are less well characterized or verifiable at depth, but such effects are legitimately under suspicion on the basis of near-surface blasting phenomenology and transient high-pressure effects of perforator jets upon cores. Compaction and pulverization and/or glazing occur, so that favorable crack-extending action by the explosive gases is prevented immediately, or permeable access to the formation is lost permanently.

The effectiveness of either explosive or hydraulic methods is reduced in inhomogeneous and kerogenitic formations by the uncertainties of geophysical logging in correctly identifying the zones having significant gas delivery potential within stimulation range of the wellbore. Explosive uniformly loaded throughout the borehole column leaves no zone untreated, but is unable to concentrate its effect in any particular interval or direction. Improved reliability in logging and interpretation methods for tight gas resources is to be expected as drilling, production, and logging experience accumulates a larger data base on such formations. Thus in the case of Devonian shale, where we know statistically that gas-bearing inhomogeneities lie close enough to wellbores to be within the modest radial access range of explosives, we are motivated to begin now to investigate advanced methods of enhancing or locally concentrating the beneficial action of wellbore-emplaced explosives, without sacrificing ultimate radial range through reduced quantity of explosive per unit vertical interval. Specifically, our approach is geometrical, rather through the route of tailored explosive impulse, which is under investigation independently.[11] We are developing shaped charges lined with uranium metal to achieve greatest penetration depth into rock. Charge sizes are designed for open-hole use and contain upward of 0.90 kg (2 lb) of explosives. Our investigations to date encompass controlled, above-ground testing methods for these charges, empirical investigations of interaction between jets and some natural and synthetic granular mineral targets, and computational design methods for the charge components themselves.

Full-Scale Testing Methods

Although controlled methods of testing shaped charges for casing perforation have long been established,[3] these charges have been so miniturized that they generally contain less than an ounce of RDX or comparable explosive. Thus the test firings can be completely contained within reusable apparatus, and the expendable targets employ ordinary sized core specimens or otherwise manageable assemblies of casing and cement. For the sizes of shaped charge with which we are involved, however, past work[4,5] aimed at exploration of mining and other excavation applications in geologic materials has been much less well standardized or refined. "Indoor" work is quite impractical, and even the procurement and handling of boulders of sufficient size to survive the after-effects of jet penetration by a shaped charge have not been uniformly satisfactory.

In our initial experiment with shaped charges having face diameters from 13.8 cm (5.4 inches) to 33 cm (13 inches), the jets were fired vertically downward into the surface of a solid rock (limestone) outcropping. The resulting penetrations were recovered by stabilizing them with poured grout and then overcoring.

Our main developmental testing, though, has been only with the smallest of these charge sizes, and with others that will also fit within a 15 cm diam (6 inch) wellbore. For this testing we have employed stacks of tightly juxtaposed grout blocks 30 cm (1 ft) thick, with steel reinforced perimeters. These blocks afford much greater uniformity and flexibility of usage than natural materials, particularly shales, of the necessary size. The stacks are readily disassembled after firing to permit observations of the penetration dimensions and the disposition of jet material. Success of this technique rests upon achievement of flat faces when pouring the blocks. By using different kinds and amounts of cement and including dense mineral powders such as magnetite (Fe_3O_4) and ferrophosphorus, we have independently adjusted either the density alone or the combined density and compressive strength of the grout to approximate the density and jet penetrability of Devonian shale. Porosity, per se, has not been matched, the porosity of Devonian gas shale being nearly zero, owing to the presence of the interstitial kerogen within the silicate-clay matrix.

Fig. 1 shows an assembled shaped charge penetrater shot ready for firing, and Fig. 2 shows the face of one of the interior blocks afterward. The grout used in the full-scale tests shown here consisted of Calseal cement, silica sand, and magnetite sand, and had bulk specific gravity of 2.50. It was weak in comparison to most rocks, with compressive strength of 500 psi.

Hemispherical Lined Cavities

The metal-lined cavities of shaped charges used for perforation of casing and in other conventional, metal-penetrating applications are generally conical in shape, albeit with the apex rounded to some appreciable radius of curvature. The explosive component of the charge is also of simple cylindrically symmetric design. It is ignited on the axis at the rear face and the detonation advances along the outside of the cone from the apex to the base, progressively collapsing the wall onto the axis and ejecting the innermost portion of the liner forward as a jet. The tip of the jet originates first from near the cone apex and the jet length increases by addition of material from farther along the liner, which is compressed to the axis later. It is characteristic of the jets from these conical charges that precise dimensional control is needed in fabricating the liner and assembling it into the explosive column, because asymmetry degrades the straightness of the jet and thereby its ability to penetrate.

Our reference shape for making highly penetrating jets is a hemispherical metal shell which is compressed simultaneously by detonation of explosive over its outer surface. This design is axially compact and thus inherently suited to fitting transversely within a wellbore. In comparison with conical charge jets, the jet from this hemispherical configuration is formed suddenly as the entire liner mass converges. A greater fraction of the metal is included in the jet, and that material at low velocity is less prone to remain intact as a slug or "carrot".

Although the explosive configuration to transform such a hemispherical liner shape into a jet is complex, we have used this sort of shaped charge for initial emperical testing of the penetration of rock and grout, in order to isolate basic effects of the liner thickness and charge standoff, varying the former first.

Figure 3 summarizes the results of five tests of penetration of weak, densified grout by 14 cm diam hemispherical, uranium-lined shaped charges at 1.1 charge diameters standoff, as a function of the liner thickness. The duplicate point with the upward directed arrow at 3.0 mm thickness represents a test in which an entire ten-block stack was penetrated. It is clear that the optimum liner thickness for this charge size is near 3 mm, and that penetration exceeding ~80% of this maximum is achieved over a broad range.

Target Materials Comparison

Concurrently with the developmental testing of full-scale, non-conical shaped charges, we have used commercial perforator charges and test methods of corresponding scale to interrelate the penetration characteristics of carbonaceous shales and our synthetic and natural rock simulants to each other. Cores of shale or other rocks are cemented into closely fitting steel sleeves which are capped by externally bolted 12.7 mm (0.5 inch) steel plates. Specimen diameters of 9 to 10 cm have been used whenever the available cores permitted it, with 6.3 mm (0.25 inch) thick sleeve walls, which did not permanently deform in the tests. Although this size and mode of encasement ofthe cores were similar to those embodied (for Berea sandstone) in API RP-43, Section 2 [3], our purpose was to compare target materials with a fixed shaped charge, rather than to test different perforator charges or the flow characteristics of fluids through the perforations. Accordingly, we conducted our tests dry (as in API RP-43, Section 1), and with the shaped charge fired in air and separated from the target rock or grout by a 24.4 mm (1.0 inch) diam drilled hole in the steel face plate. After firing and removal of the end plates, the sleeve was readily slit diametrically and the perforated specimen split open for examination of its geometry, state of compaction and other trauma, presence and condition of jet debris, etc. Fig. 4 shows such penetration in two specimens of Devonian shale, both oriented perpendicular to the natural bedding, as determined by the available cores.

Table 1 summarizes our comparative penetration data obtained by this method, using Welex D.P. HT-1 charges, in several specimen types involved in this study. Several results are indicated:

(1) Among the rocks and the stronger grout, the penetration depths are within the range 160 ± 35 mm.

(2) The limestone representative of the outcrop site used in our initial full-scale text is the least penetrable of these targets.

(3) The weak magnetite grout used as the target for optimizing uranium liner thickness (Fig. 3) is more than twice as penetrable as the shales.

(4) The dense, high strength grout is a satisfactory target material for simulating the penetration behavior of shale.

Experience accumulated with several sizes and designs of conical casing perforator shaped charges, mostly in the API RP-43, Section 2 test setup, or in simulations thereof for deep, high-strength or high-stress situations, [6,7] provides a basis for assessment of our penetrability results. The primary parameter with which penetrability of Berea sandstone and both stronger and weaker limestones has been correlated is their brittle compressive yield strength [4]. Our weak, magnetite grout evidently extends the experience to even weaker material than the outcrop Austin limestone (chalk).[9] Although the sufficiency of the semi-logarithmic correlation [8] may be open to question when extended to much higher strengths such as we are experiencing in our very low-porosity shale and limestone specimens, the utility of the prior data base lies in the fact that for each target material included [8], the same ratios of penetrations have generally been achieved among a given range of perforator charges. We may utilize this emperical systematization, and our data from Table I, Fig. 3, and our full-scale hemispherical charge test with 1.5 mm liner thickness to estimate the penetration depth to be expected into Devonian shale with such a charge. This computation is traced in Table II. Constancy of the ratio of penetrations by the two charges is seen to be ± 15% from the mean for two materials whose penetrabilities are more than a factor of 3 apart, and bracket that of gas bearing shales.

Advanced Cavity Design

To fulfill the need for a high-performance jet to attack difficultly penetrable, tight formations, we are developing an advanced uranium-lined shaped charge design for open-hole use. This design has the same sort of simple jacketed explosive shape as is used with a conical liner. However, the liner is smoothly curved in a comparatively shallow cavity. It is thickest on the charge axis and tapered toward the rim, so that the advancing detonation front accelerates progressively thinner metal to progressively higher velocities. The result is similar to that achieved by the hemisperical charge described in an earlier section. There is nearly simultaneous convergence of the liner onto the axis, and rapid formation of a jet containing a large fraction of the liner mass, leaving little possibility of formation of a slug. Even greater latitude in dimensional tolerances are admissible than with the hemispherical system.

Whereas the shape of a conical liner is basically specified (but for the rounded apical region) by the cone angle and wall thickness, and the hemispherical system likewise by the radius and thickness, the tapered liner for forming a jet is not simply parameterized. Nor is its motion to be analyzed mathematically in closed form. High speed, high storage computer treatment of the two dimensional hydrodynamics of the explosive and metal system is used to select and optimize liner contours for fabrication and testing.

Computations were made for four tapered uranium liner shapes for a charge having 10.0 cm external diameter and 10 cm length, such as to fit within a 15 cm (6 inch) diam hole. The liner contour calculated to deliver the jet in this system was selected on considerations of jet momentum and stability, and prospects for operation at small standoff. It is characterized at the rim by an inner radius of 40 mm and thickness of 1.35 mm, an angle of intersection between the inner surface and the face plane of 89°, and at the apex by an inner radius of 44 mm and thickness of 2.67 mm. Its total mass of uranium is 335 g, and at completion of the calculated jet formation dynamics, 39 µs after firing, 135 g is directed along the axis at velocities between 1.0 and 5.9 km/s.

Fig. 5 shows the contours of the liner, explosive, and steel outer jacket, together with computed contours of the deformed liner at times of its flight just before peak convergence and acceleration, and just after relaxation of the peak pressures and attainment of the ultimate axial velocity distribution. These contours, in proper spatial separation, are circumscribed by a hypothetical 15 cm (6 inch) diam wellbore. Subsequent elongation of the jet, in air and hopefully in rock, will occur as a kinematic consequence of the range of velocities imparted to the jet material within the motion pictured.

Remaining Problem Areas

Velocity Threshold for Penetration

The finding that Devonian shale and indeed many other brittle rocks have such a combination of dynamic compressive strength and lack of porosity as to be among the less penetrable of gas-bearing rocks is not adequately understood in relation to the penetration of compartively ductile metal targets by shaped charge jets. It is widely accepted that the penetration of metals is described by simplistic hydrodynamic principles, whereby penetration depth, P, is proportional to jet length, L, and the square root of the ratio of density of jet to target metals. The adequacy of this theory is predicated upon the verified existence of a threshold velocity for penetration of each target metal, or combination of target and jet, such that jet length, L, is reckoned by excluding material having velocity below the threshold. For a copper jet penetrating steel, the threshold of 2.0 km/s is quite meaningful. The next important question for our experimental investigation of the low penetrability exhibited by rock is the presence and magnitude of a threshold velocity. The techniques and devices reported above now enable us to proceed to investigate this matter productively.

Standoff

Another factor known to influence the penetration of metals by shaped-charge jets is the separation between the faces of the charge and target, or standoff. In wellbore applications, standoff of more than a few cm would call for special emplacement measures such as underreaming. The influence of standoff upon the performance of jets, particularly those of uranium metal, in penetrating rock remains to be established, and the status of our investigations now permits this to be done effectively for our designs.

Mechanics of Rock Penetration

Prior studies of the penetration of rock[4,5], mostly by jets of copper and iron, have indicated the operation of several mechanisms associated with production of the hole into the rock. These include: (1) primarily lateral displacement and rearrangement of the matrix of porous rocks, so as to reduce the porosity and accomodate the macroscopically displaced materia close to the hole without introducing significant residual stresses (2) ejection of excess material in an annular countercurrent surrounding the central jet; and (3) embrittlement and introduction of strain energy into the deformed rock, which is later relieved spontaneously by crumbling in hard, nonporous rocks in the regions of a cone-shaped entrance crater and along the unstable walls of the hole. The latter two effects are more extreme. These mechanisms relate to the state of the rock-hole interface after the penetration, and indeed to the flow capacity between the penetration and a surrounding homogeneous formation. However, the intended application of jets in tight formations is dependent upon intersecting of secondary natural or subsequently induced fracture channels, so the direct, localized effects upon the rock matrix will be bypassed. What remains to be understood is the relation between the alteration mechanisms manifested in the remaining rock and the dynamic resistance to penetration.

We expect to make progress in computationally modeling the dynamics of rock penetration by jets, but the realism of the models will be subject to verification by the observable geometry of the holes and microstructural alteration of the adjacent rock.

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FIGURE CAPTIONS

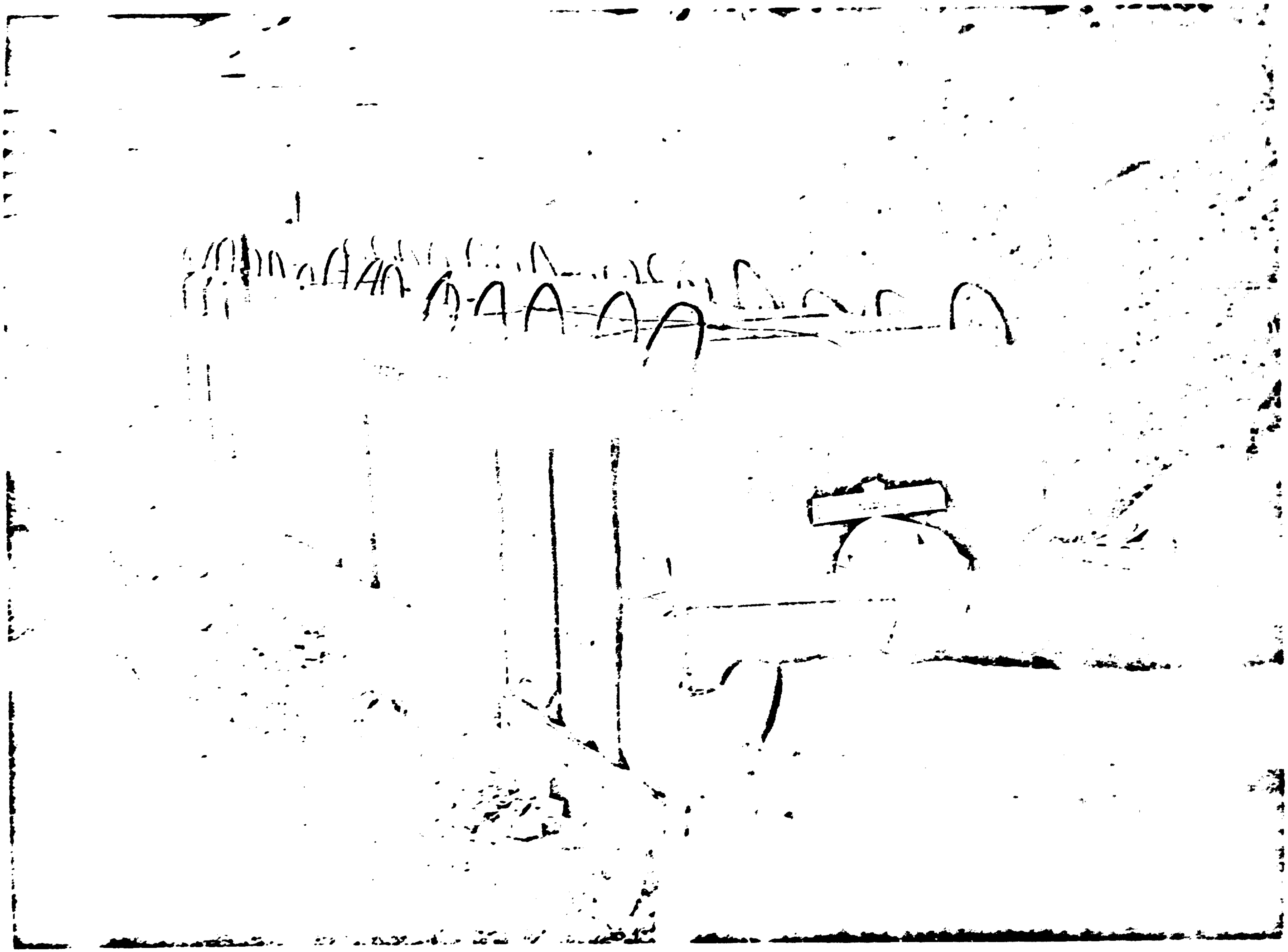
Figure 1 Grout blocks and shaped charge assemblies for test of jet penetration.

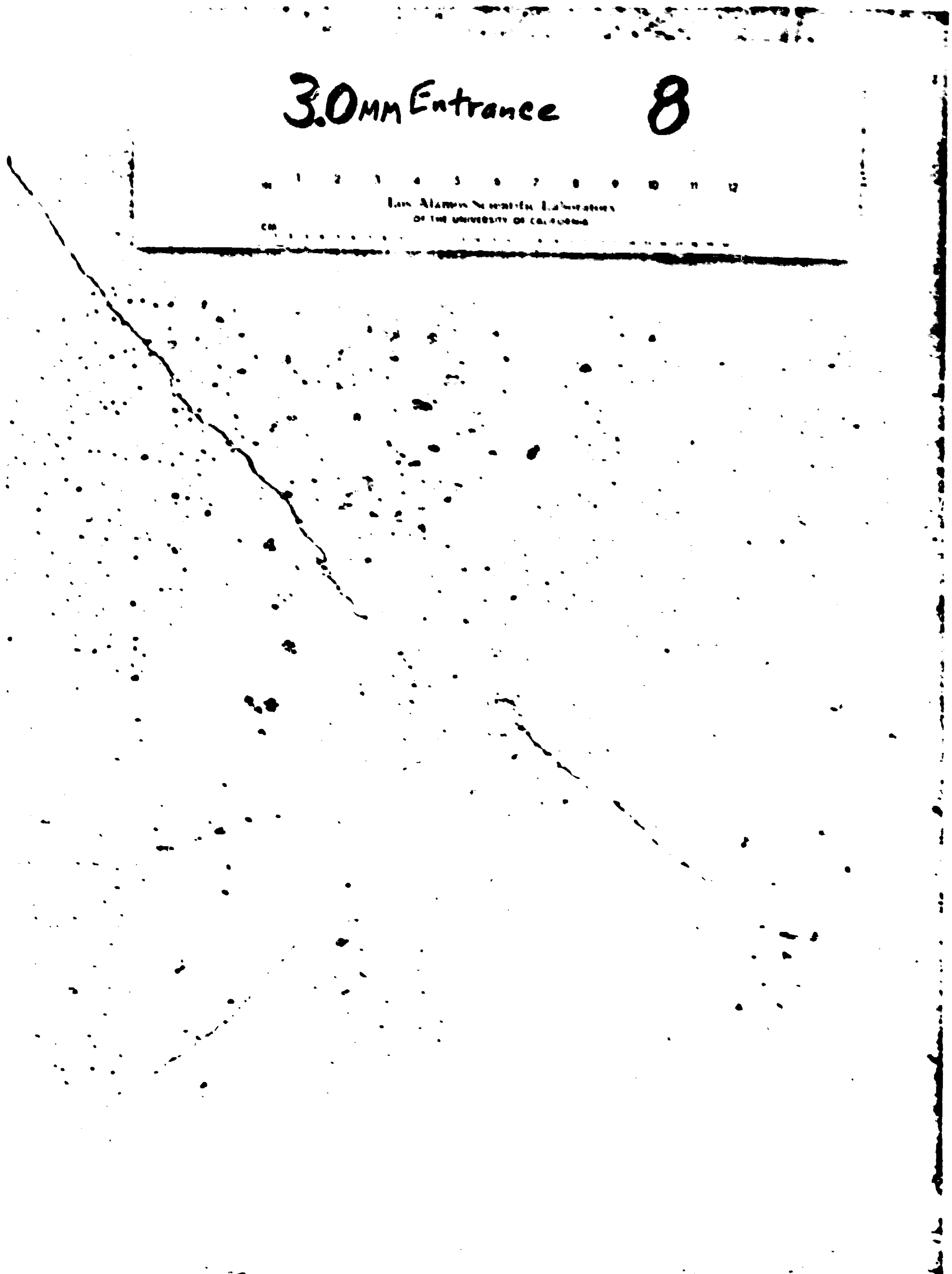
Figure 2 2 cm diam hole made in entry face of eighth block, 2.13 m (7.00 ft) into stack shown in Fig. 1a, by 14 cm diam hemispherical charge with 3.0 mm thick uranium liner. Total penetration was 2.75 m (9.02 ft).

Figure 3 Dependence of grout penetration upon uranium liner thickness for 14 cm diam (5 1/2 in diam) hemispherical shaped charges. First experiment with 3.0 mm (0.119 inch) liner, shown with upward arrow, penetrated 3.05 m (10 ft) stack completely. Solid point represents test in Figure 1.

Figure 4 Penetrations into carbonaceous Devonian shale cores by 32 mm (1.26 inch) diam commercial perforator charge (copper-lined cone, for 3 1/8 inch gun, API RP-43, Sect II Berea Penetration.)

Figure 5 Section of 10 cm (4 inch) "square" shaped charge design having tapered uranium liner. Initial configuration of steel-jacketed HMX explosive is shown centered in 15 cm (6 inch) circle, with computed liner contours before firing and during jet formation at 20 μs and 30 μs after firing.

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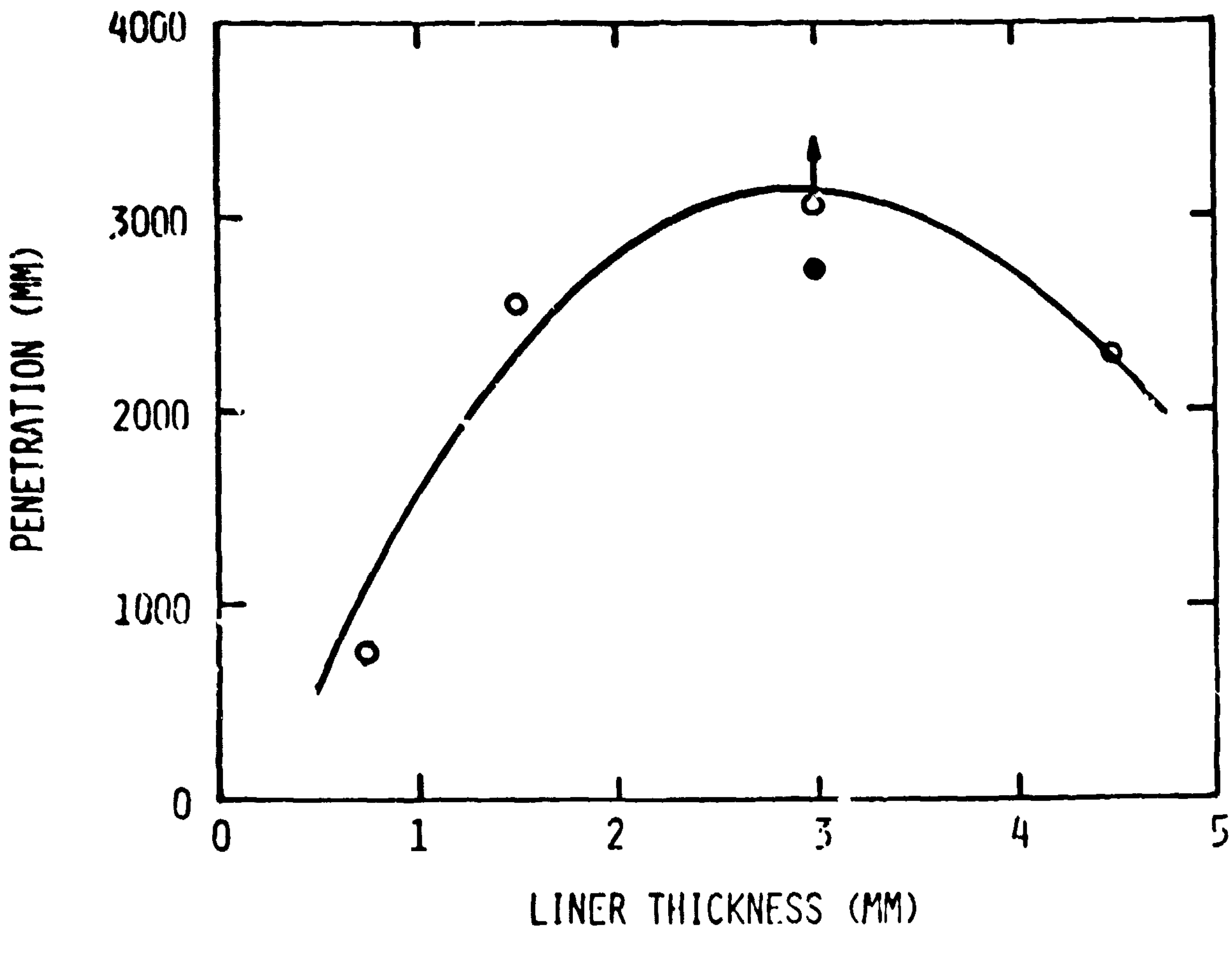

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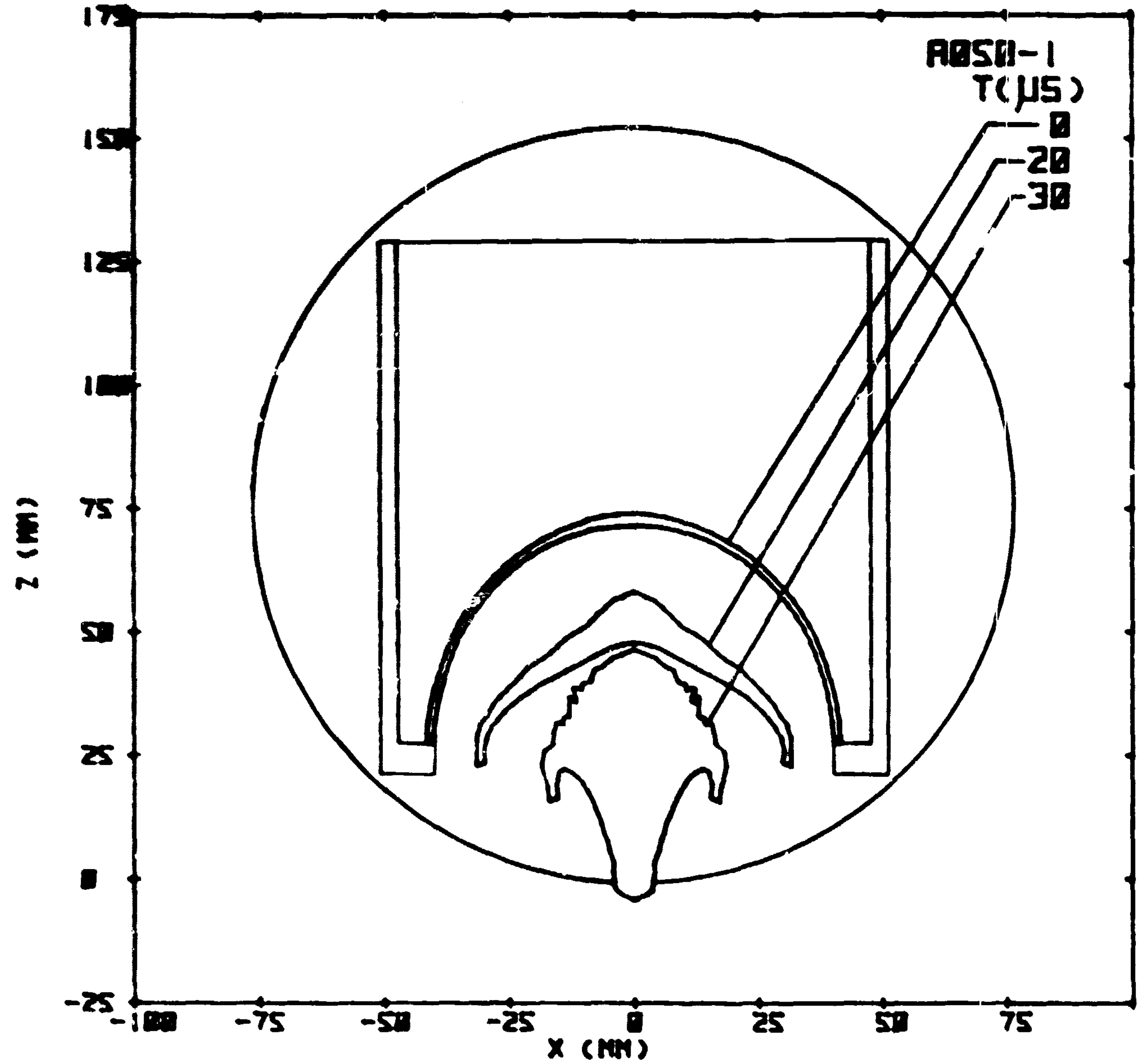
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TABLE I: JET PENETRATION OF DRY TARGET MATERIALS BY 32 MM DIAM PERFORATOR CHARGE

Material	ρ g/cm^3	Y_0 MPa(ksi)	Penetration Depth mm
Appalachian Devonian			
Shale A	2.55	57 (8.3) $\parallel$ [a]	140
Shale B	2.65	109 (15.8) $\perp$	150
Antrim Shale[b]	2.37		165
Limestone (Nevada Test Site)	2.72		125
Fe_3O_4/Cement Grout	2.50	3.4 (0.5)	356
FeP/Portland Grout	3.62	60 (8.8)	195

[a]Mean data from Ref. 10 for same brown shale interval of core from offset well in Lincoln CO, WV (Columbia Gas Transmission Co. #'s 20402 and 20403); and $\parallel$ and $\perp$ denote parallel and perpendicular orientations, respectively, if bedding planes to compression axis of samples.

[b]Core specimens furnished by Dow Chemical Co., Midland, MI.

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TABLE II: PENETRATION DEPTHS OF SHAPED CHARGES INTO TARGET MATERIAL

Charge	Limestone	Weak Grout	Devonian Shale
32 mm diam cone (standoff/diam=0.4)	125 mm	356 mm	150 ± 10 mm
138 mm diam Hemisphere (1.5 mm liner) (1.1 standoff/diam 1.5)	685 mm	2540 mm	945 ± 150 mm
Ratio of Penetrations	5.5	7.1	6.3 ± 1